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Laser Ignition of Liquid Propellant XM46: Ignition of Larger Volumes

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Abstract

Studies of the laser ignition of the liquid gun propellant XM46 have been extended to volumes up to 30 cm^3 of propellant. In the first part of this work, a multistage initiator was designed and tested, patterned after earlier electrical ignition designs. The study then proceeded to attempt direct ignition of 5 cm^3 and 30 cm^3 of the liquid. Although marginally successful, these studies demonstrate the difficulty of igniting these amounts starting from atmospheric pressure in open vessels.

ACKNOWLEDGMENTS

This study could not have been done without extensive discussions and encouragement from James DeSpirito and John D. Knapton, Weapons Technology Directorate, U.S. Army Research Laboratory (ARL). Funding was provided by the Office of the Project Manager, Crusader.

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1. INTRODUCTION

Previous reports of the laser ignition of XM46 propellant in our laboratory have documented our characterization of the basic parameters of the process (Beyer 1996) and the first attempts to extend this technique to gun igniters (Beyer, DeSpirito, and Reeves 1996). Those studies were limited to devices with volumes of 0.1 and 1.0 cm^3. In the present study, the effort toward a practical device was continued with a 17-cm^3 multistage "initiator" filled with a total of 5 cm^3 of propellant. This device uses ignition of a small chamber and transfer to larger volumes. Difficulties with the operation of this design and its inherent complexity led to the subsequent studies of direct ignition of 5- and 30-cm^3 volumes of propellant.

2. APPARATUS

Two similar neodymium:glass lasers operating at 1.054 nm with nominal output energies up to 50 J were used. Most of the studies were done with a pulse length of 0.9 ms (10% points); the tests shown for the 30-cm^3 chamber were performed using the 0.5-ms pulse length laser. We have not observed a major difference in the ignition behavior with these two lasers. However, with these energies and pulse lengths, operation is close to the damage threshold for the sapphire windows, so the longer pulse is generally preferred.

For the initiator studies, which were an extension of the work reported earlier (Beyer, DeSpirito, and Reeves 1996), the laser energy input was through an optical fiber. The fibers used were either of 1.0-mm or 1.5-mm core diameter. As was mentioned in that earlier report, an effort remains necessary to make fibers useful for this application. Connector lifetimes and survival of the fiber optic in the chamber during the transient ignition event are the main limitations. No connectors were used for these tests, and the fibers into the chambers were replaced after five tests or more frequently. For these reasons, the follow-on studies were done mostly with sapphire windows. However, sapphire is subject to absorption from nonlinear optical processes (not purity related) and is easily damaged by the lasers in use here. Window damage was usually avoided if the spot size entering the window was at least 3 mm in diameter and the window was kept meticulously clean. The latter requirement is not always easily achieved in a range area. In most cases, the laser energy was focused to a spot inside the propellant. While XM46 has no measurable absorption at the laser wavelength (Marrs 1993), we have demonstrated that there is a nonlinear absorption with the present lasers when focused. In a limited number of cases, with either a

solid graphite target or a suspension of powdered graphite in the propellant, a quasi-parallel beam of approximately 3-mm diameter was used. While no dramatic differences were seen, the dependence on energy density was not explored in these experiments.

The multistage initiator device was modeled after the comparable two-stage component of the electrical ignition fixture designed by Martin Marietta Defense Systems (Hanson 1993). It has three chambers of increasing volume, 0.1 cm^3, 1.54 cm^3, and 16.1 cm^3, respectively. Each chamber vents tangentially into the next larger chamber. The smallest chamber is a 0.63-cm-diameter (0.25 in) cylinder of the same length. It is shown schematically in Figure 1. The light from the fiber optic enters the curved wall opposite the graphite target. One end of this chamber has a confinement/vent orifice diameter of 0.9 mm, about 1.5 mm long. Made of tantalum, it showed no evidence of wear after more than 30 shots. The face of a Kistler 607C pressure gauge formed the opposite end wall of this chamber.

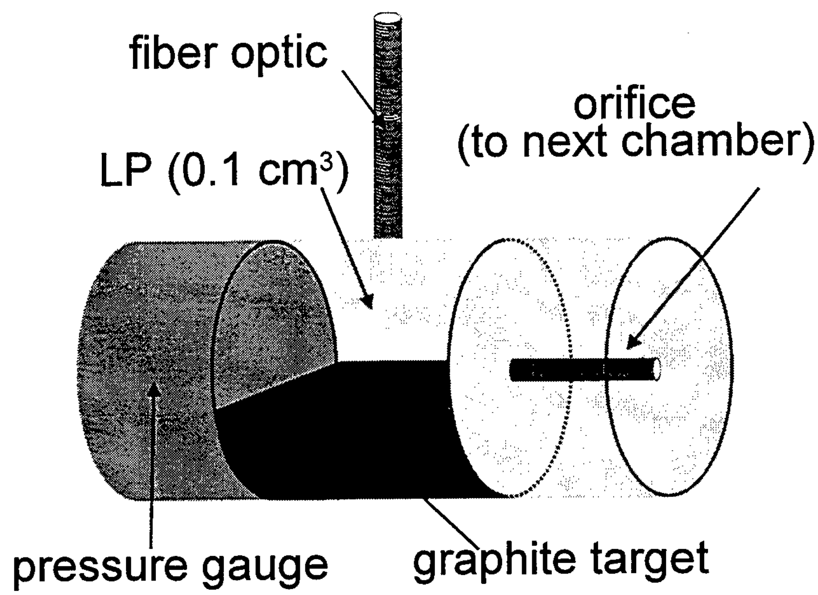


Figure 1. Schematic of first chamber of multistage initiator.

The second chamber was a cylinder 1.27 cm in diameter (0.5 in) and 0.79 cm (0.313 in) long with a 1.27-cm-diameter (0.5 in) hemisphere at the output end. The vent of this chamber was 3.2 mm in diameter (0.125 in) and 1.9 cm (0.75 in) long. As designed, the first two chambers were to be completely filled by injection of the propellant into the smaller chamber. The large chamber, which was never tested, was to have a lower loading density, with a fill of less than 5 cm^3 of propellant anticipated.

The first of the vessels designed to explore the direct ignition of larger volumes is shown schematically in Figure 2. It is a simple extension of the design used extensively in our multitude of small

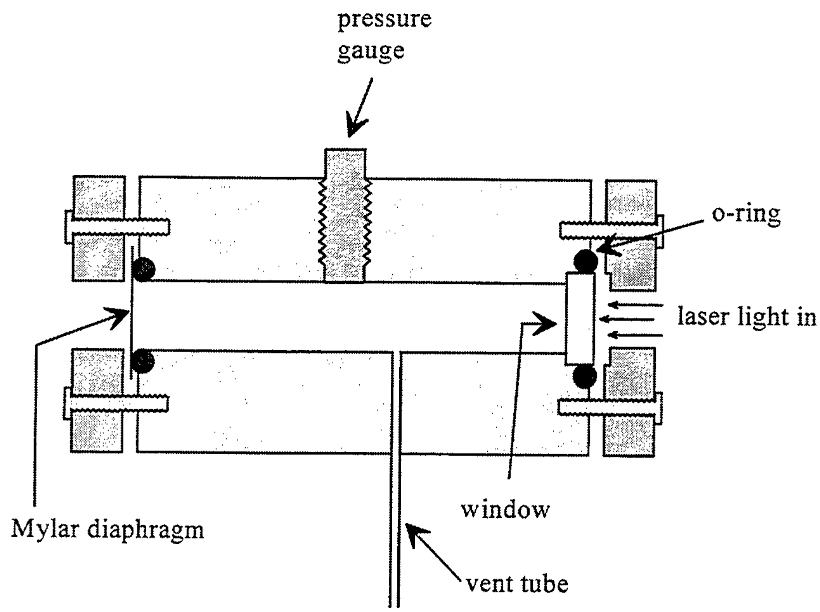


Figure 2. 5-cm^3 test vessel.

chambers in the earlier studies (Beyer 1996; Beyer, DeSpirito, and Reeves 1996). The interior diameter is 0.95 cm (0.375 in) and approximately 6.3 cm (2.5 in) long. It was fabricated from Ph 13-8 Mo steel, but was not heat treated. It has a window and Mylar burst diaphragm that are sealed with o-rings and clamps. The pressure gauge (Kistler 211 B) serves as the primary diagnostic tool. The 7-cm-long, 1-mm-i.d. vent tube shown was not present for all tests. Its main purpose was to ensure that a test started at atmospheric pressure, since this device readily pressurizes the propellant upon assembly. This vessel was essentially duplicated in acrylic without the pressure gauge for the photographic observations.

The larger (30 cm^3) vessel (stainless steel Ph 13-8 Mo, heat treated to about R45) is shown in Figure 3. Its interior chamber is 2.54 cm (1.0 in) in diameter and 6 cm (2.38 in) long. The vent is 0.79 cm (0.313 in) in diameter and 3.8 cm (1.5 in) long. Pressure is sealed with an o-ring at low pressure and a tapered metal seal for higher pressures. The window and pressure ports are both designed to accommodate Kistler 607C pressure gauges. Not shown is the simple clamp used to hold a Mylar diaphragm or breakaway window over the top of the vent in some tests.

3. OBSERVATIONS

3.1 Three-Stage Initiator. In spite of difficulties with the fiber optic input system, good results were obtained for ignition of the 0.1-cm^3 first stage. The key successes were the achievement of reliable ignition and a reduction of the extreme peak pressures commonly seen with the present electrical ignition

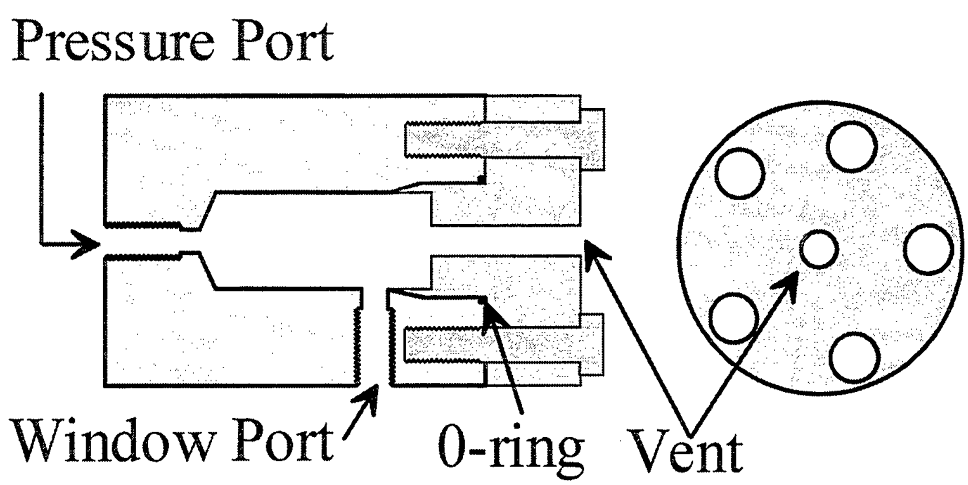
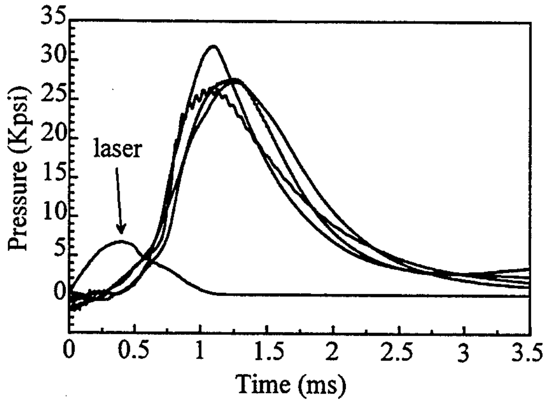


Figure 3. 30-cm^3 test vessel.

fixture. Reproducibility was quite good, as shown in Figure 4, where four consecutive shots are shown. For this series, nothing was done to the chamber except to open the fill valve and inject the propellant. As can be seen, besides some minor oscillations, the pressure repeatability is good. Also, the peak pressures ca. 170 MPa (25 ksi) are in a range to remove many concerns of material problems in critical regions of the design such as check valves on the fill system.

Following our successes with the first stage, several attempts were made to characterize the transfer of ignition to the second (1.5 cm^3) chamber. At the same time, an effort was made to build and operate a remote fill system, which it was hoped would speed progress. Our expectations that this system would be simple to get operational were not met. Relatively few successful shots were fired. A typical "success" is shown in Figure 5. In this figure, the initial peak pressure of the first chamber is somewhat higher than in Figure 4, the result of deliberately depositing more laser energy to ensure ignition. Two characteristics stand out in these traces. Most significant is the magnitude and the oscillations of the pressure in chamber two. Also of note is that the highest pressure seen by the primary chamber is due to back pressure from the secondary chamber when it ignites. Thus, there may be limited value to keeping the first pressure rise low. The secondary chamber pressure trace shows indications of undesirable ignition, especially the pressure spikes for almost 0.5 ms before the major pressure rise.

These characteristics led to the conclusion that a major effort in understanding ignition transfer might be necessary to make this device work well. The additional difficulties with the fiber optic input designed into this fixture were mentioned earlier. Thus, this effort was delayed pending the delivery of fiber optic solutions being pursued under contract (General Fiber Optics, Inc. 1993).



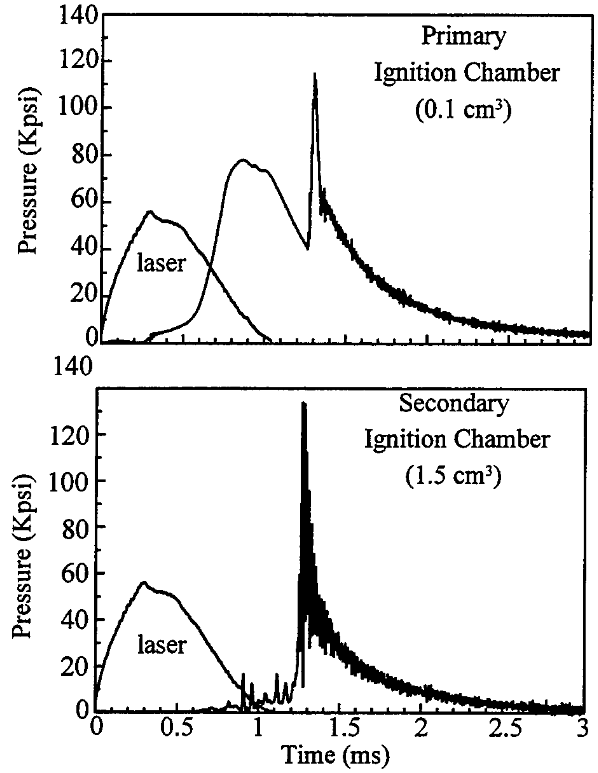
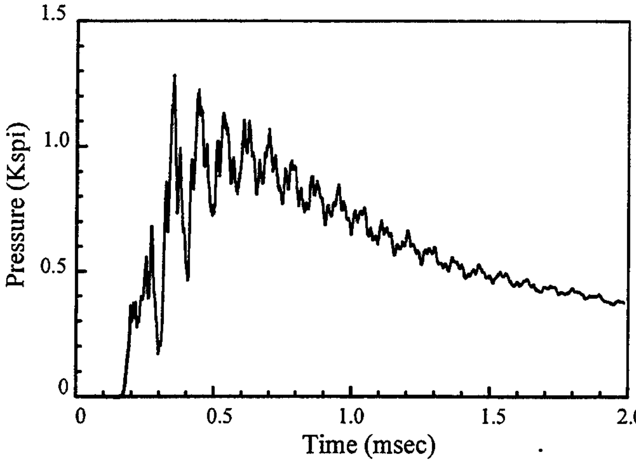


Figure 4. Pressure-time records in first stage of initiator from four consecutive shots.

Figure 5. Pressure-time records from initiator when two stages are ignited.

3.2 5-cm^3 Chamber. One of the major unknowns in going to a larger chamber is the influence of pressure waves resulting from the initial laser energy deposition. This phenomenon was explored with a large number of shots with both water and propellant in the chamber. As with the smaller chambers, it is usually the case that when there is robust ignition, there are minimal pressure waves during the pressure rise. However, cause and effect are not clear here. Two examples of less-than-ideal behavior are shown here for water shots. Figure 6 was done with no vent tube and starting from 1 atmosphere pressure. The laser beam was focused to a spot about 1 cm inside the window. As can be seen, the pressure rises during most of the laser pulse and then decays slowly. The magnitude of the pressure waves, especially during the pressure rise, is certainly enough to affect the ignition event. Although efforts were made to completely fill the chamber, the presence of small air bubbles cannot be ruled out and may be a contributing factor to the lower frequencies. A large gas bubble was observed after the event, but was expected from vaporization of water by the laser.

When the water was doped with graphite powder (ca. 2 mg/cm^3), even more dramatic behavior was observed some of the time. A typical pressure trace is shown in Figure 7, which was done with the vent



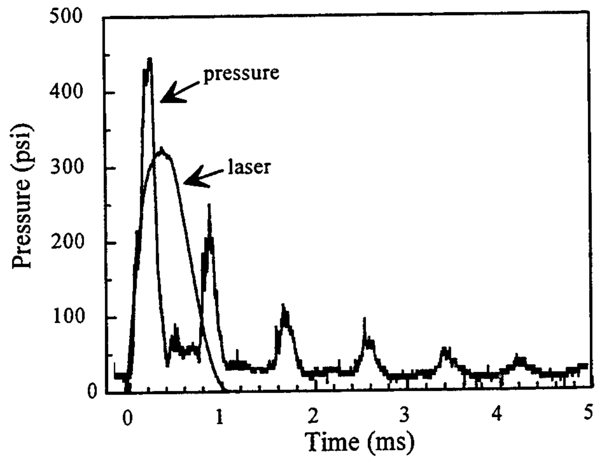


Figure 6. Water shot in 5-cm^3 chamber.

Figure 7. Water doped with graphite in 5-cm^3 chamber.

tube mounted on the vessel. Most dramatic is that there is no pressure rise during most of the laser pulse. It appears that the graphite may be reflecting a large portion of the laser energy after an initial absorption, as indicated by the pressure rise. The dominant (slow) frequency is possibly related to the motion of the liquid in the vent tube. Traces quite similar to this have also been recorded with propellant heavily doped with graphite. The addition of the graphite, when used, was kept to small amounts following these observations.

Many successful ignition events were observed with this vessel. One of the characteristics of focusing the laser into the clear liquid is the randomness of response. While this may be due to impurities, it may also be caused by other variables such as changes in the laser mode structure and subsequent differences in nonlinear absorption. A limited number of high-speed film records were made with the acrylic chamber in an attempt to determine how extensive the ignition point is in these events. The film records are limited but show no dramatic difference in light intensity or distribution between using a solid target a few millimeters inside the window or light doping with graphite. In both cases, ignition appears to take place in a small region. With no target, ignition was observed to occur within a centimeter of the window.

One very clear observation, as with our earlier, smaller scale studies, is the dominance of prepressurization in the ignition of XM46. In this vessel, it is easy to prepressurize up to several hundred pounds/$inch^2$ (a few Megapascals) just by filling and tightening the screws for sealing the o-rings. The

lack of ignition reproducibility has so far prevented quantification of the pressure effect. An additional observation is that, because ignition takes place near the window, and the vent (burst disk) is at the opposite end, flow through the vessel from ignition point to vent provided sufficient confinement so that the propellant was often not extinguished upon burst of the diaphragm. The continued burning most frequently happened following an ignition delay, as discussed in the next sections.

Two related observations are shown in Figure 8. Although part of the trace is missing, the pressure is clearly rising in (B). The acoustic report in the laboratory was dramatic from this event. Two characteristics are seen in this and other events that continued to burn: a longer time delay and a higher peak pressure before diaphragm burst. Both events were done with a 0.5-ms laser pulse of approximately 30 J of energy (estimated energy reaching the propellant). Both started at pressures of about 200 psi (1.4 MPa). As can be seen, in event (A) the laser energy couples in better, the pressure rise is higher during the laser pulse, and the ignition delay is shorter. In the initially less robust shot (B), apparently a larger flame kernel or volume of reaction develops before the diaphragm bursts so that sufficient gas generation is present to continue the combustion with the chamber vented.

Similar behavior is shown in Figure 9. Again, in (A) the prompt ignition is detrimental to continued combustion. Though it takes most of a millisecond to complete, the chemistry is turned off by the depressurization. Prepressurization on both shots was measured at less than 100 psi (0.7 MPa). Clearly, full combustion is present in (B). Although no measurements of pressure rise were made in the dump vessel, the amount of unburned propellant recovered after (B) was much less than 5 cm^3.

3.3 <u>30-cm^3 Chamber</u>. The results with the 5-cm^3 chamber suggested that with moderate prepressurization, a burst disk to allow reaction propagation to a critical extent, and modest confinement in venting the combustion products, a significant amount of propellant could be burned from direct ignition. The result was the design and construction of the 30-cm^3 chamber.

The initial experiments were done with no prepressure. The laser light was introduced through a window mounted in the side port, according to the chamber design. Although full ignition was not expected without some temporary confinement (diaphragm equivalent), the vent was left open to the air to determine the level of response in this configuration. Typical pressure traces showed maximum levels of up to 200–300 psi (1–2 MPa). Attempts to deposit more laser energy and to tighten the focus spot in the propellant resulted only in many burned windows. Even with a Mylar diaphragm glued over the vent,

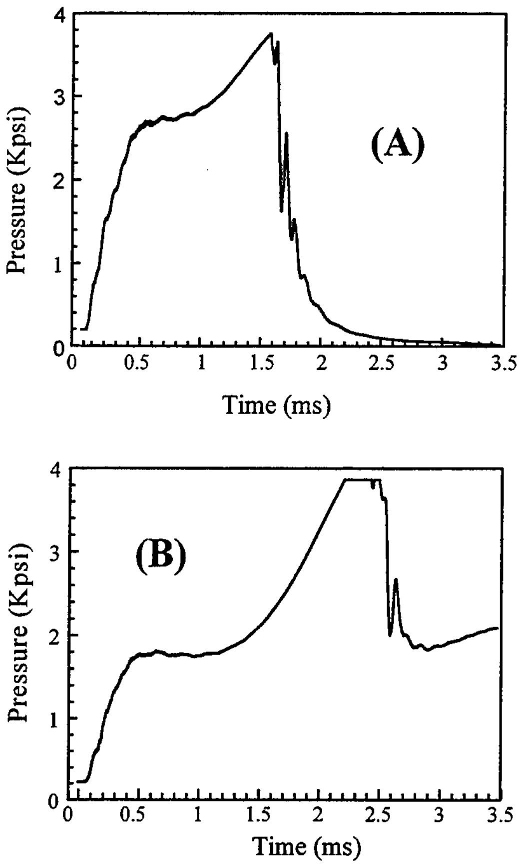


Figure 8. XM46 laser ignition in 5-cm^3 vessel showing depressurization resulting in (A) extinction and (B) continued burning.

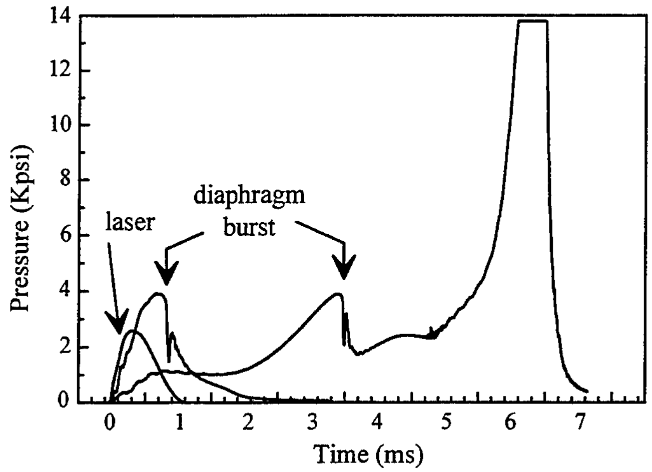


Figure 9. XM46 ignition in 5-cm^3 vessel showing laser pulse, prompt ignition, and delayed ignition.

pressure rises did not vary much. Thus it was made clear that a major difficulty was to ensure that the chamber was completely filled with liquid. Inspection of partial fills showed that the liquid was not wetting the walls well and that many air bubbles remained.

Since prepressurization is the key to easy ignition of XM46, two such shots were tried with this chamber. In both shots, the side port was used for adding nitrogen gas pressure at 600 psi (4 MPa). Since the Mylar we use is only partially transmitting at the laser wavelength, it tends to burn above about 10 J of energy and is therefore not useful as a window here. Disposable windows were cut from fused silica substrate and clamped over the top of the vent hole. Clearly, igniting the propellant near the top of the vent will not result in a condition where there is sufficient confinement to maintain the pressure required for combustion. However, this arrangement allowed us to demonstrate ignition of the volume without waiting for modifications to the chamber.

The pressure result of the second of these shots is shown in Figure 10. As expected, there was no continuing pressure after the window released the initial pressure. Of note is the slow rate of pressure buildup after the laser pulse, following the 4-ms "induction period." Following this event, the chamber was completely empty except for ca. 1 cm^3. Some ejected liquid showed evidence of partial reaction, but no analysis was made. It also appears that the pressurization rate (from 6 ms to 10 ms) is about one-fifth the comparable rate with the smaller chamber. This effect could perhaps be due to either gas bubbles in the volume or the compressibility of the liquid (Liquid Propellant XM46 Handbook 1994). Based on the 5-cm^3 vessel results, there is not much doubt that a significant amount of the propellant would have burned in the chamber if ignition had taken place below the vent tube, as originally designed.

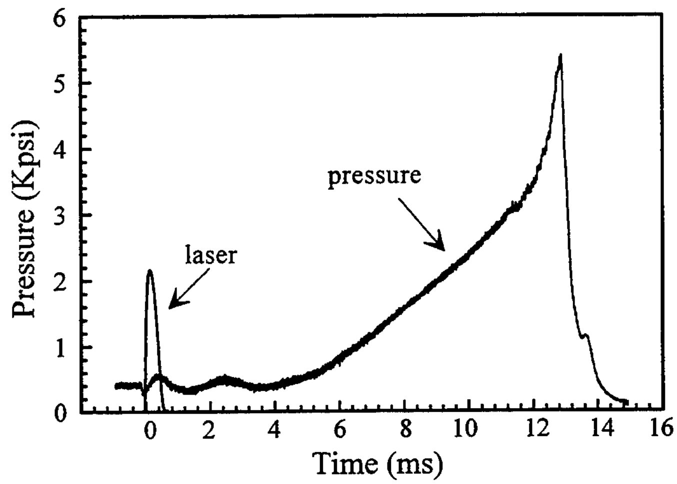


Figure 10. Pressure response during ignition of 30-cm^3 of XM46.

4. DISCUSSION

The studies with the multistage initiator show the wisdom of using this method of igniting liquid propellant. The advantage has been demonstrated earlier of igniting a sufficiently small initial volume so that a complete fill can be used to get rapid pressurization; by limiting the volume to ca. 0.1 cm^3, burnout occurs before extremely high pressures are reached. In past designs, the difficulties we have observed here in ignition transfer to larger volumes have been avoided by making the ratio of volumes small. The conclusion from the present study is that, while we might be able to engineer around these difficulties, some better systematic understanding of the control of the process would be valuable. It appears that this approach will work and was set aside primarily to wait for the fiber optic solutions.

The larger volume chambers demonstrate that, with a proper pressure release valve and modest prepressurization, a volume of 30 cm^3 can be readily ignited directly with the deposition of ca. 30 J of laser energy. Since it appears that less-than-prompt ignition is advantageous, smaller amounts of energy (laser or electrical) may work reliably in a well-designed device. The design of an appropriate valve has not been attempted.

5. FUTURE STUDIES

Clearly, this present study is incomplete in many respects. Pending the availability of funding, attempts will be made to more clearly characterize the initiator behavior with three chambers loaded. The value of the direct ignition studies would be increased by experiments that couple them to a sealed dump chamber to measure the fraction of liquid propellant burned. It would also be valuable to characterize this approach more carefully for the effect of prepressurization and the amount and rate of deposition of energy.

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APPENDIX:

THE EFFECT OF LIQUID COMPRESSIBILITY ON PRESSURE RISE

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If the liquid propellant (XM46) were an incompressible liquid, then the ignition would be much more independent of the initial volume of propellant. Although efforts were made in this study to distribute the laser energy over a larger volume, the energy deposition remains a local event. The result of this event is the creation of a thermally hot region (probably a plasma when a liquid-solid interface is involved), with some gas-phase products produced during the laser pulse. These gas-phase products are the source of the pressure rise that is important in the ignition process. Since the ignition reactions appear to have a strong pressure dependence (not necessarily the same dependence as the burning rate exponent), a good initial pressure rise yields a short ignition delay and usually more reproducible ignition. Conversely, if the pressure does not rise sufficiently, a long delay or no ignition will result. The principal effect of a larger volume of propellant is to reduce the pressure rise in the chamber through compression of the liquid.

From the Liquid Propellant XM46 Handbook (1994), for increases in pressure of this magnitude, the density changes are described by:

$$\rho = \rho_0 \exp \{-2.02 \times 10^{-5} * \text{pressure}\}$$

with the pressure in bar. For these calculations, $\rho_0 = 1.46$ g/cm^3 was used.

From our observations, the maximum pressure rise for a 0.1-ml chamber is about 17 MPa (2,500 psi). From the compressibility data for M46, if we assume that a simple gas bubble has formed, the bubble volume would be about 0.3 µl. Using this same equation, the graph in Figure A-1 is generated. The largest volume plotted is 30 ml, with a corresponding pressure rise of 7 psi (50 kPa). Although the observed pressure jumps in the 30-ml chamber were somewhat larger, up to 1.3 MPa (200 psi), the difficulty of direct ignition where pressure must be generated during the laser pulse is clearly a formidable task. In addition, the importance of a completely filled volume (free of pressure-absorbing air bubbles) remains the same as the volume becomes larger.

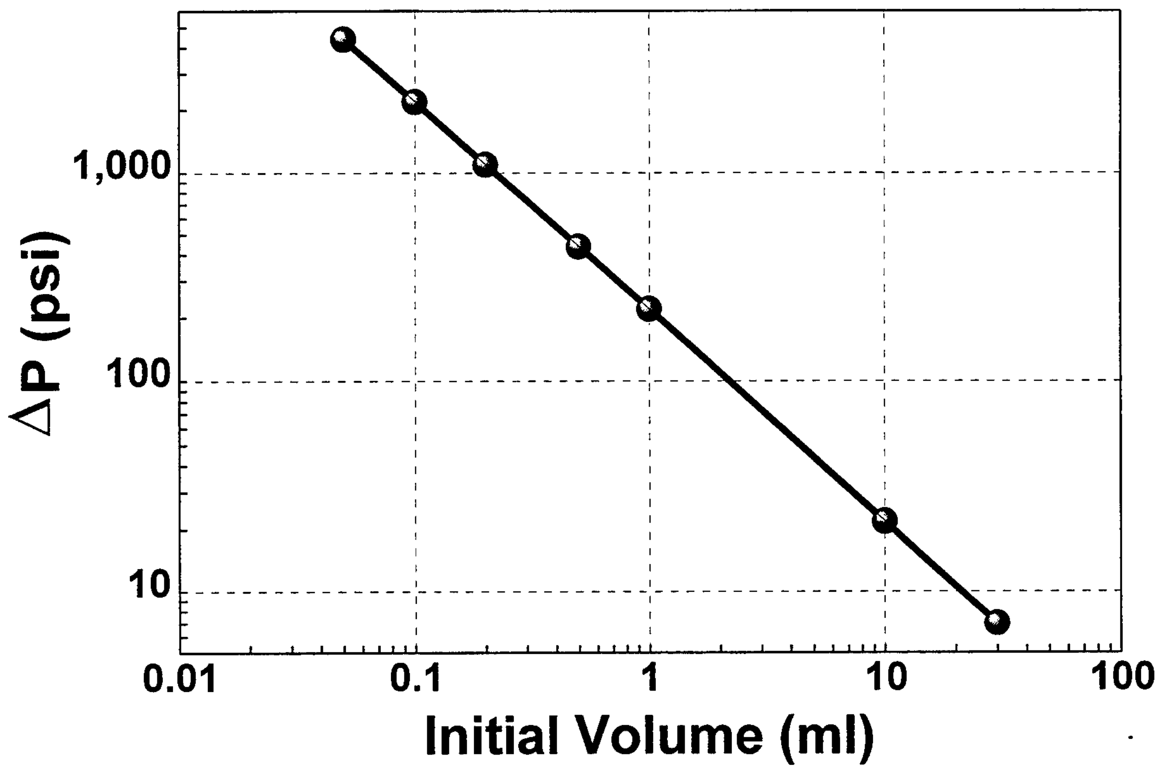

Figure A-1. The effect of a decrease in volume of 0.3 µl with a chamber filled with XM46.

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Studies of the laser ignition of the liquid gun propellant XM46 have been extended to volumes up to 30 cm^3 of propellant. In the first part of this work, a multistage initiator was designed and tested, patterned after earlier electrical ignition designs. The study then proceeded to attempt direct ignition of 5 cm^3 and 30 cm^3 of the liquid. Although marginally successful, these studies demonstrate the difficulty of igniting these amounts starting from atmospheric pressure in open vessels.

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